3-D RUPTURE SIMULATIONS FOR FAULTS WITH COMPLEX GEOMETRIC SEGMENTATION: COLLABORATIVE RESEARCH WITH SAN DIEGO STATE UNIVERSITY AND UNIVERSITY OF CALIFORNIA, RIVERSIDE

Award Number 02HQGR0009
Final report for 8/1/01 – 7/31/02
June 18, 2003

Program Element: Research on earthquake physics, occurrence, and effects

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Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 02HQGR0009. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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Technical Abstract

We use the three-dimensional finite element method to model the dynamics of an earthquake on a fault with complex geometric segmentation: the 1999 M 7.1 Hector Mine, California, earthquake. In particular, we focus on the effect of the branched structure in the north of the fault system on the propagation of rupture and slip. A superficial static analysis might imply that only one of the two northern branches should undergo slip in this event, because slip on one segment should push the other segment into a stress shadow. However, in this earthquake, rupture started on the north branch, which did not rupture through to the surface of the earth. Rupture then subsequently propagated to the northwest branch, as well as to the remainder of the fault system in the south. Our dynamic models of this earthquake indicate that rupture propagation to the northwest branch is a natural consequence of the observation that rupture did not proceed to the earth's surface on the north branch. The region of the northwest branch that overlaps with the non-slipping surficial region of the north branch is brought to failure by slip on the more deeply buried part of the north branch. Experiments with different stress configurations and hypocenter locations show that the results are insensitive to the details of our physical modeling parameters. The results help to emphasize that the observed rupture and slip patterns we see in earthquakes are due to a complex interaction of fault geometry and stress pattern.

Non-Technical Abstract

The dynamics of faults with complex geometric segmentation are likely to be strongly affected by this geometrical complexity. As an example of such a system, we perform numerical (computer) models of the 1999 M 7.1 Hector Mine, California, earthquake, which took place on a branched fault system. Our models of this event help to explain a curious observation in this earthquake: both northern fault branches slipped, even though slip on one would be expected to prevent slip on the other. We find that the key reason this complicated slip pattern was possible was that the slip on one of northern branches of the fault did not extend completely to the surface of the earth. With the slipping regions of the two fault branches not completely overlapping, slip was allowed to propagate to the other branch. The results help us to understand how both fault geometry and the initial stress pattern can contribute to the final rupture and slip pattern in an earthquake, including determining which fault branches slip.

Introduction

The 1999 M 7.1 Hector Mine, California, earthquake provides a unique opportunity to study the dynamics of faults with complex geometric segmentation. This earthquake took place on a branched fault system in the Easter California Shear Zone (Scientists from the USGS *et al.*, 2000), as shown in Figures 1a and 1b. The hypocenter of this event was on the north branch, while the mapped surface rupture was on the northwest branch and the branches to the south. While slip occurred at depth on the north (hypocentral) branch, there is no evidence of surface slip on this branch (Scientists from the USGS *et al.*, 2000; Hauksson *et al.*, 2002; Ji *et al.*, 2002; Kaverina *et al.*, 2002; Simons *et al.*, 2002). This slip pattern presents somewhat of a puzzle, because it would appear from a superficial static analysis that slip on the north branch should bring the northwest branch into a stress shadow, preventing rupture on that branch. Our dynamic models for this event help to show why this seemingly improbable slip pattern took place, and help to show the important effects of both fault geometry and stress pattern on the rupture and slip processes.

Method

We use the 3-D finite element method (Whirley and Engelmann, 1993; Oglesby, 1999) to perform numerical models of the Hector Mine earthquake. This method assumes that the earth is an elastic solid. A fault is represented as a collection of split nodes in a finite element mesh; these nodes experience frictional forces in addition to elastic forces. These frictional forces in turn are calculated from a slip-weakening friction law (Ida, 1972; Andrews, 1976). The Physical and computational parameters are summarized in Table 1, and our finite element mesh is shown in Figure 1c. We perform many models with different initial stress patterns and hypocentral locations. The key difference is between models that allow slip to proceed all the way to the surface on the north branch, and those that do not.

Results

We find that if we use relatively uniform initial stresses on our fault system, rupture proceeds all the way to the surface of the earth on the northwest branch, and does not proceed at all to the northwest branch (Figure 2). Both of these features are in conflict with observations. In this case, the fault displays the characteristics that one would expect from a simple static coulomb failure analysis: If the north branch slips over its entire area, almost the entire northwest branch is in a stress shadow, and is thus brought further from its failure stress level.

There are many possible ways to keep slip on the north branch from extending all the way to the earth's surface, in agreement with observations. We make the simple assumption that the shear stress in the top 1 km is zero on this branch. This assumption can be somewhat justified by arguing either that the surface part this segment is very weak, or that it already slipped in a recent earthquake. Dynamic models with this assumption produce a slip pattern very different from that of the more homogeneous stress models. Slip dies out near the surface of the north branch, and proceeds to the northwest branch (Figure 3). Note that by making an assumption that allow us to match one aspect of the real earthquake (the lack of surface slip on the north branch), the model naturally produces a result that matches the second important aspect of this event (propagation of slip to the northwest branch.

The reason for the above result is rooted in the dynamic and static stress field radiated by slip on the north branch. Parts of the northwest branch that roughly overlap the slipping region of the north branch are brought farther from their failure stress. However, parts of the northwest branch that don't overlap with the slipping region of the north branch are brought closer to their failure stress level, and are actually brought above their failure level near the fault branch. It is here, near the fault branch, where rupture jumps from the north branch to the northwest branch.

Experiments with many different stress patterns and hypocentral locations show that the above results are not sensitive to the fine details in our models. In particular, the results remain essentially unchanged for hypocenters at the branch region and south of the branch region. Similarly, the depth of the non-slipping region on the north branch is also not critical. All that is required for rupture to propagate to the northwest branch is a certain degree of non-overlap (misalignment) between the slipping region of the north branch and the northwest branch.

In addition to the main result above, we also find that in this case of geometrical fault complexity, the final stress pattern is highly heterogeneous, even though the initial stress patterns are almost entirely homogeneous. This final stress pattern is shown in Figure 4. The geometrical discontinuities in the fault geometry manifest themselves as regions of stress accumulation or reduction on the fault. These residual stress patterns may have a large role in the subsequent evolution of slip over multiple events, and are the subject of ongoing work.

Conclusions

We find that through simple, yet rigorous dynamic models of the 1999 Hector Mine earthquake we can explain the somewhat puzzling observation that slip propagated to both fault branches in the north of the fault system. The results are robust with respect to hypocentral location and stress pattern. We also find that from an originally smooth initial stress distribution, the complex fault geometry produces a highly heterogeneous final stress pattern. The results help to emphasize that the rupture dynamics and slip pattern of faults with complicated geometry are a result of the interaction between fault geometry and stress pattern. Unfortunately, the results also imply that it may be difficult to predict future patterns of slip from fault geometry alone. To produce a realistic slip models for purposes such as seismic hazard analysis, many models with different assumptions about initial stress field (and most likely frictional properties as well) must be performed.

Papers produced under USGS support

Oglesby, D. D., S. M. Day, Y.-G. Li, and J. E. Vidale (2003). The 1999 Hector Mine earthquake: the dynamics of a branched fault system, *Bull. Seism. Soc. Am.* **Under Review**.

Data Availability

All simulation results are available upon request from the principal investigator:

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The finite element modeling code is also available to investigators who are members of the Lawrence Livermore National Laboratory Methods Development Group collaboration program.

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Table 1. Material and computational parameters

Density	2800 kg/m3
V_P	6300 m/s
V_S	3600 m/s
Initial shear stress (north segment)	130 bars
Initial shear stress (northwest and south segments)	177 bars
Initial normal stress (north segment)	-200 bars
Initial normal stress (northwest and south segments)	-287 bars
Static frictional coefficient	0.7
Sliding frictional coefficient	0.5
Fault element size (north segment)	500 m X 500 m
Fault element size (northwest and south segments)	532 m X 500 m
d_0	0.4 m
Maximum Frequency	~0.6 Hz

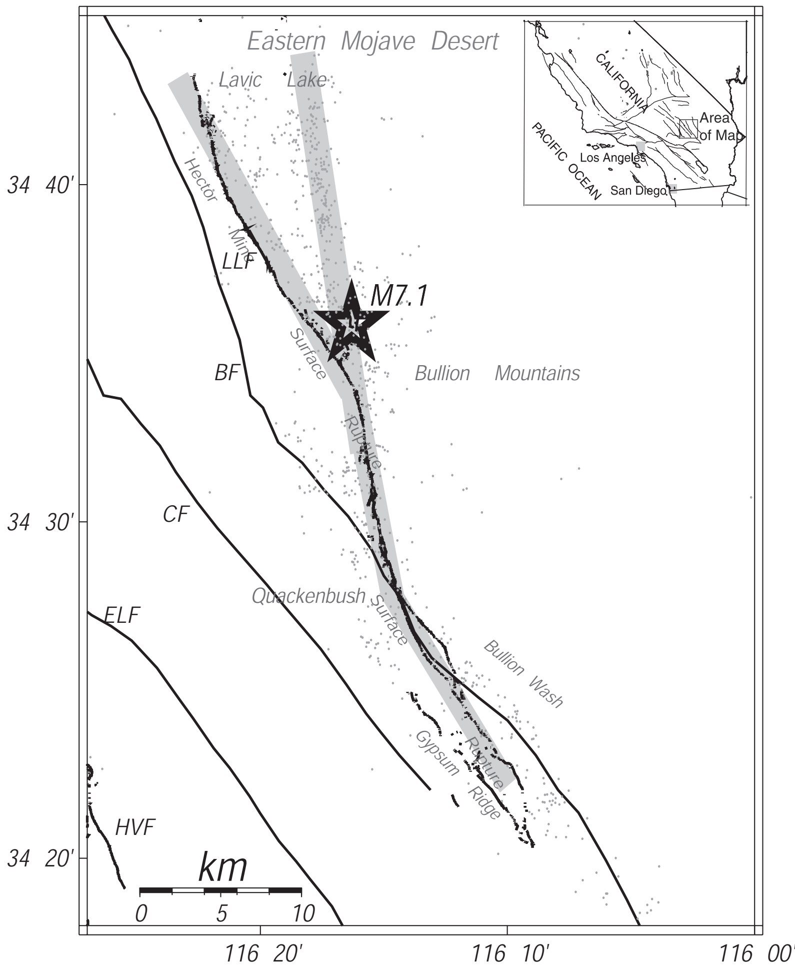
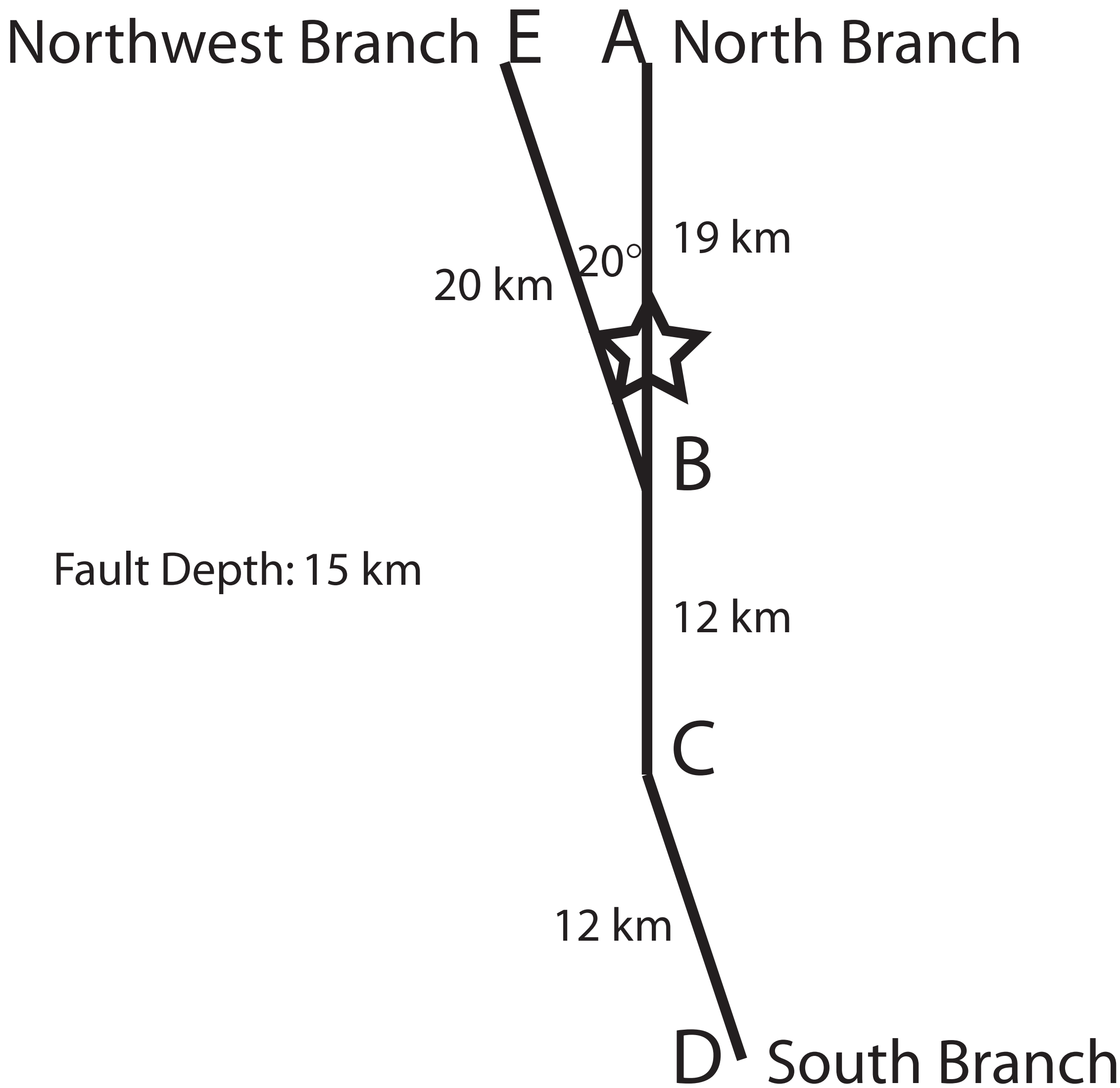

Eastern Mojave Desert
Lavic Lake
Hector Mine
LLF
M7.1
BF
Surface Rupture
Bullion Mountains
CF
Quackenbush Surface
ELF
Bullion Wash
Gypsum Ridge
Rupture
HVF
km
0 5 10
34 40'
34 30'
34 20'
116 20'
116 10'
116 00'
CALIFORNIA
PACIFIC OCEAN
Los Angeles
San Diego
Area of Map

Figure 1a.



Northwest Branch
E
A
North Branch
19 km
20°
20 km
B
Fault Depth: 15 km
12 km
C
12 km
D
South Branch

Figure 1b)

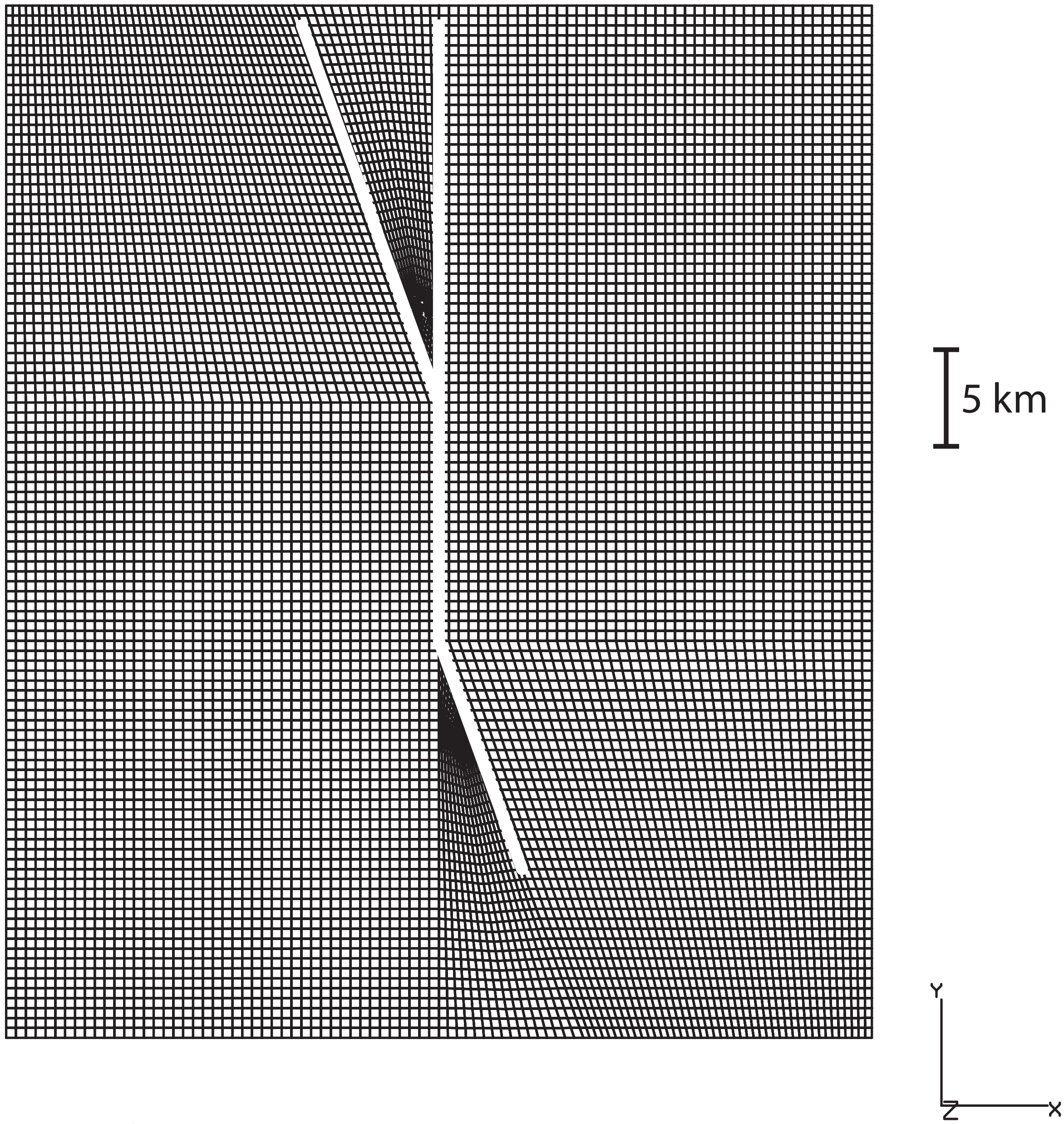
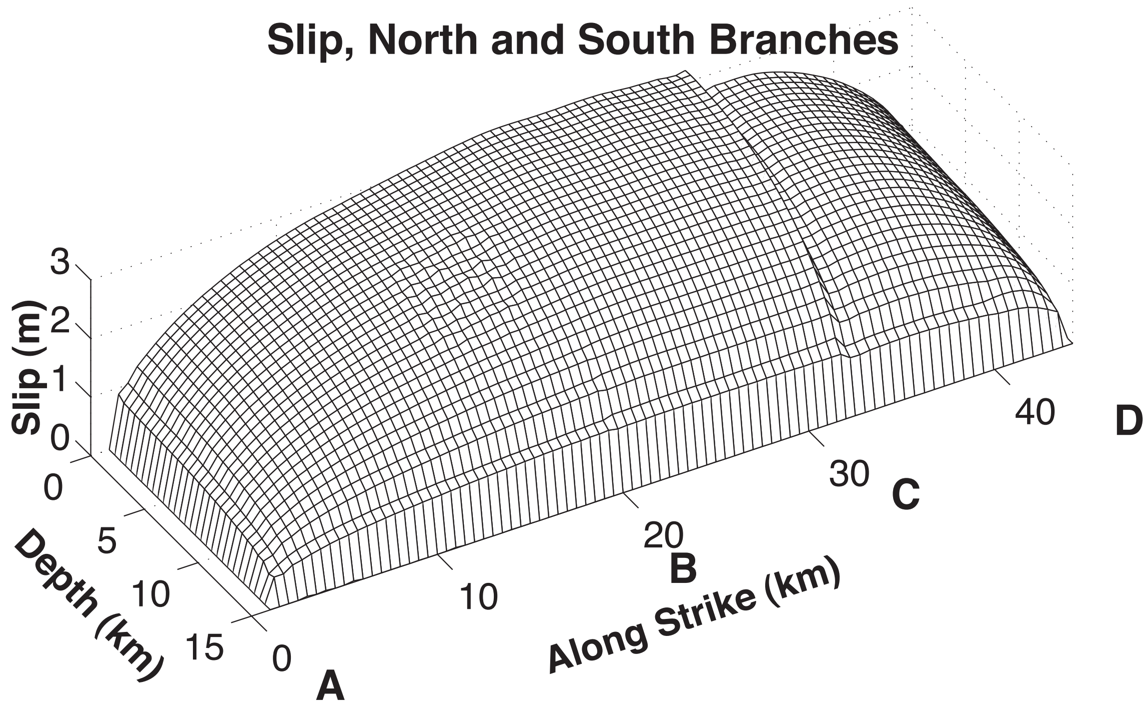


Figure 1c)

Figure 1. a) Fault geometry used in the dynamic models. Map of the 1999 M 7.1 Hector Mine earthquake, including mapped surface rupture (rough dark lines), mapped nearby faults (smooth dark lines), inferred branched fault geometry (thick gray lines), epicenter (star), and aftershocks (dots). After Li *et al*. (2002) and Scientists from the USGS *et al* (2000). b) Map view of fault geometry. Segment names are identified, with the preferred hypocenter marked with a star. The letters denote a set of reference points along the fault system. c) Map view of finite element mesh used in dynamic models. Fault segments are shown in white. This mesh is surrounded by a larger buffer region to eliminate spurious reflections of seismic waves from the model boundaries (not shown).



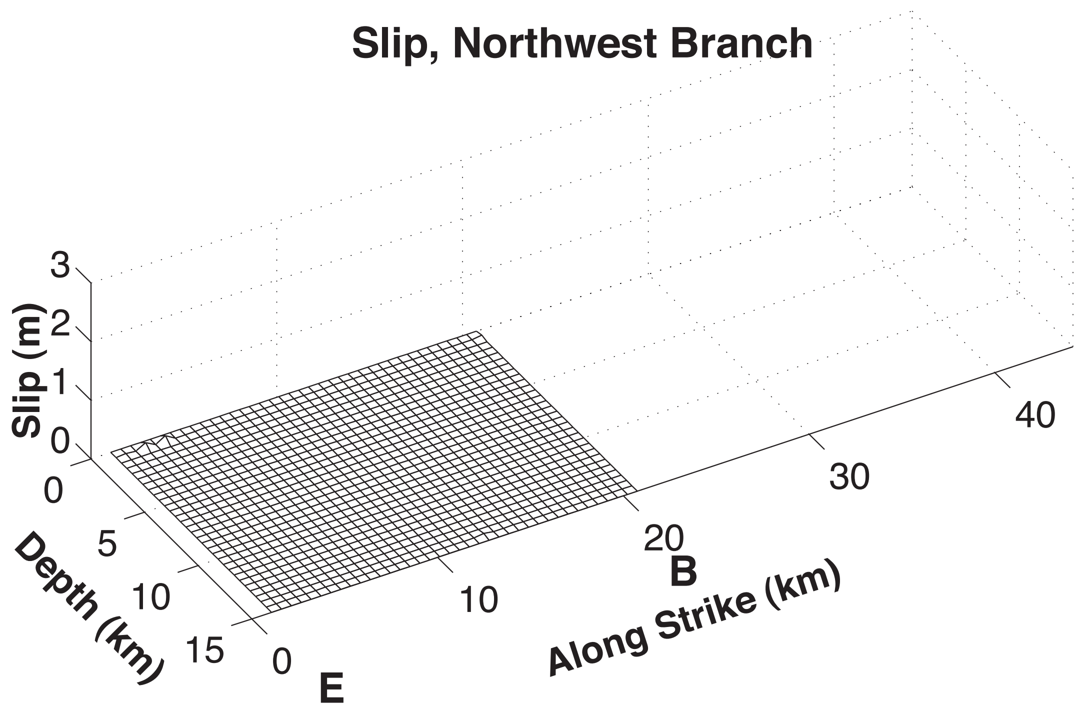
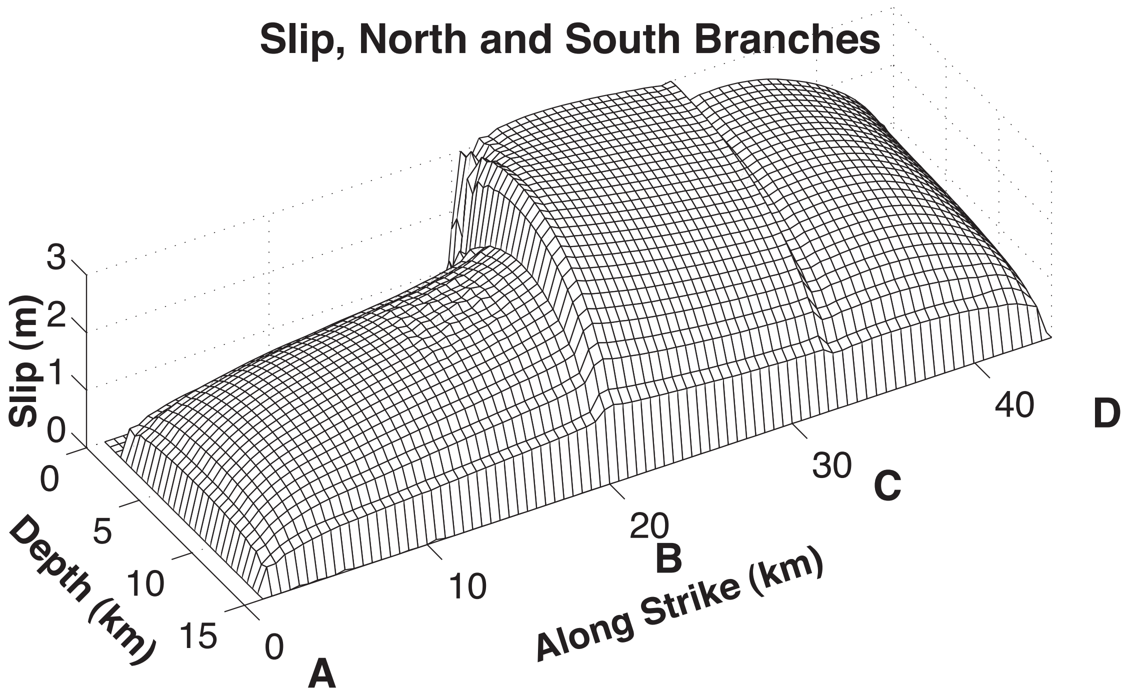


Figure 2. Final slip for the model in which rupture proceeds to the surface on the north branch. Locations corresponding to A through E on Figure 1b) are marked. In this model, rupture nucleates on the north branch, and does not proceed to the northwest branch.



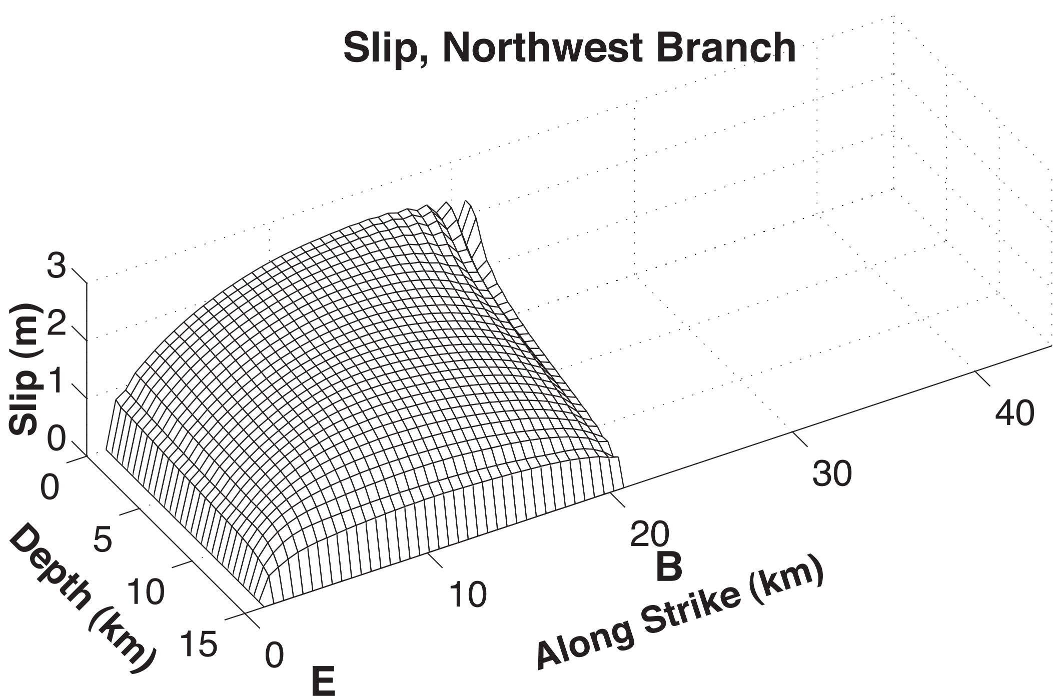


Figure 3. Final slip for the model in which rupture stops 1 km from the surface on the north branch. Locations corresponding to A through E on Figure 1b) are marked. In this model, rupture nucleates on the north branch, and has propagated to the northwest branch by 5.6 s into the simulation. By the end of the simulation, all segments have slipped.

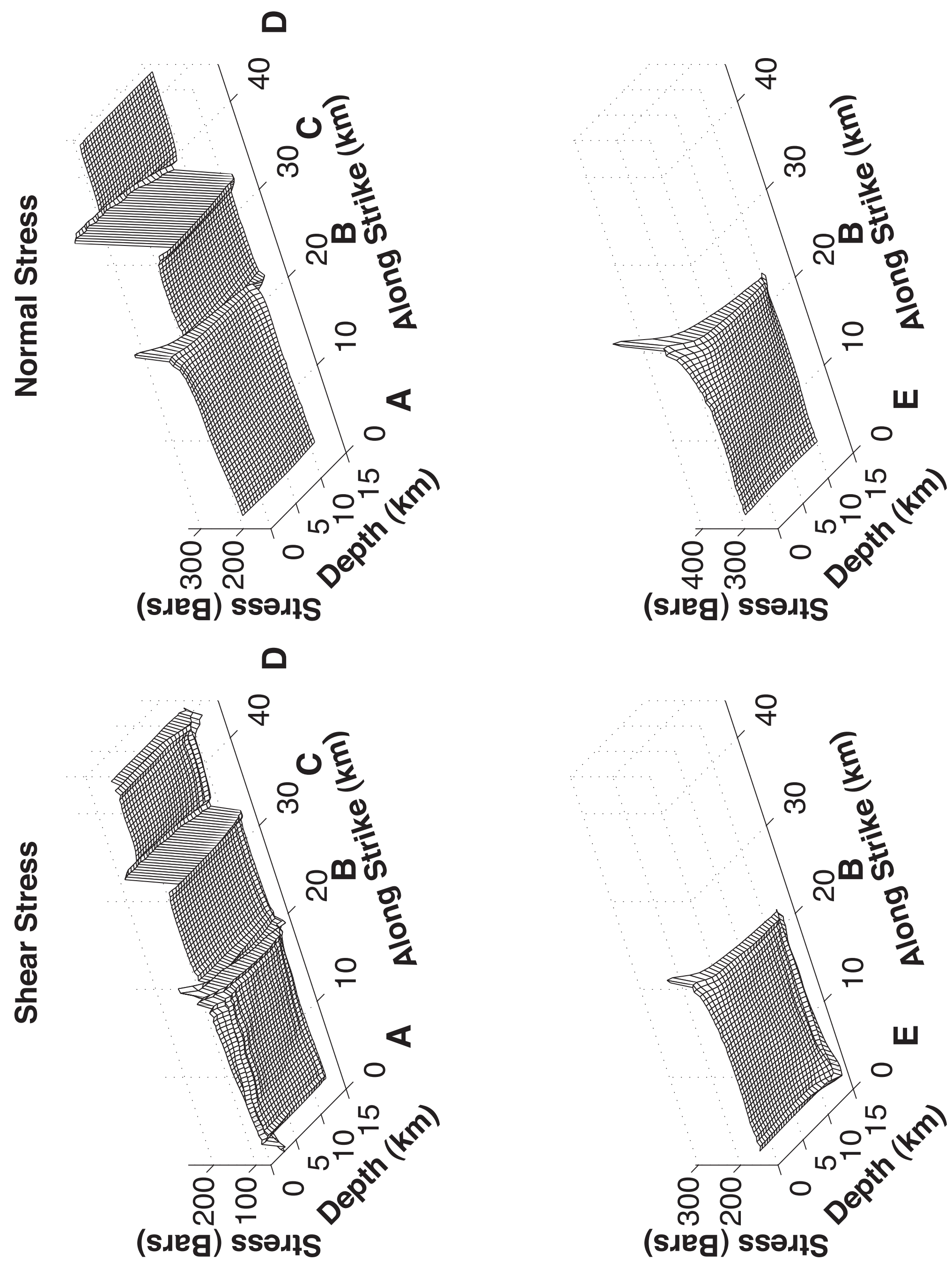


Figure 4. Final modeled stress on the fault for the model in which rupture stops 1 km below the surface on the north branch. Locations corresponding to A through E on Figure 1b) are marked. Shear stress is displayed on the left panels, and normal stress is displayed on the right. The north and south branches are displayed on the top panels, and the northwest branch is displayed on the bottom. In this model, rupture nucleates on the north branch, and has propagated to the northwest branch by 5.2 s into the simulation. By the end of the simulation, all segments have slipped. Note the highly heterogeneous final stress pattern.